The global ocean circulation: an elegant dynamical system

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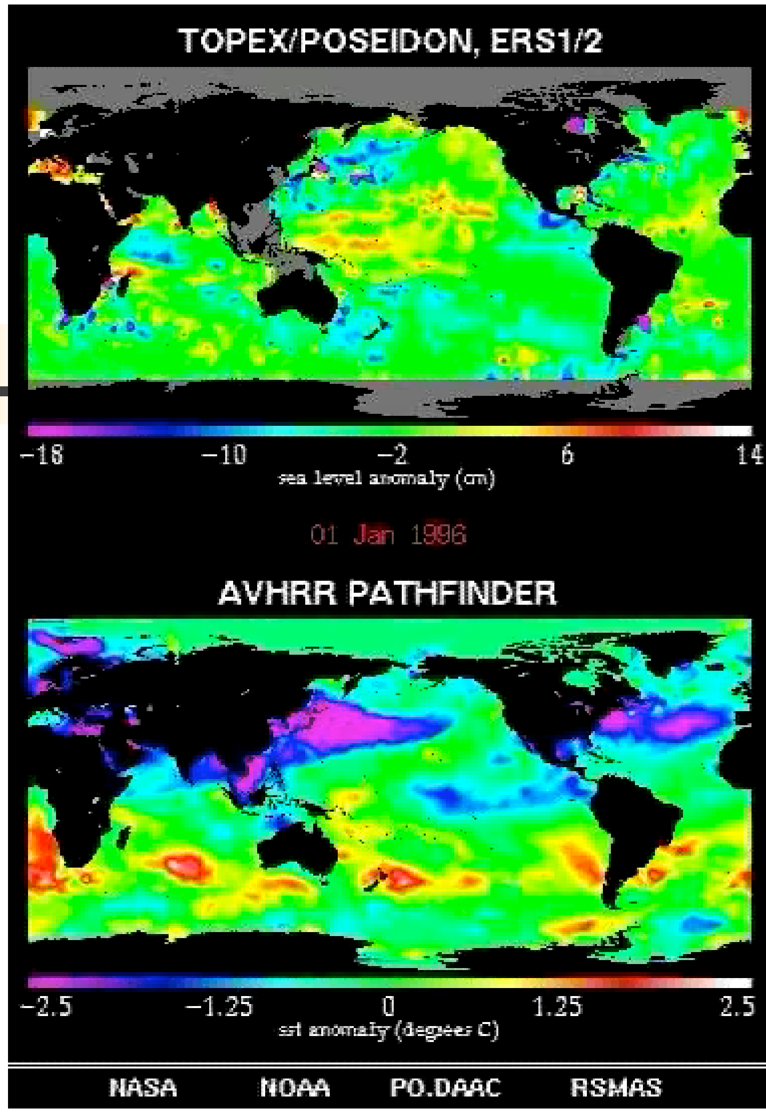
Variability at the ocean surface



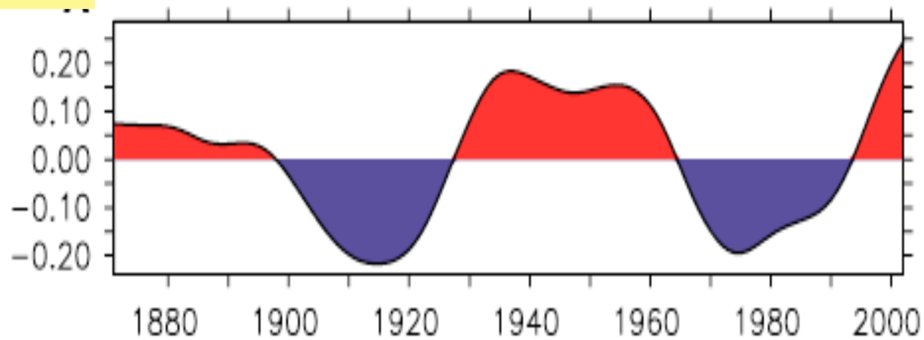
Sea surface height anomaly
Jan 1996 - Nov 1999
Scale -18 cm to +14 cm

Sea surface temperature
anomaly (SSTA)
Jan 1996 - Nov 1999
Scale -2.5 C to +2.5 C

Courtesy NASA/JPL-Caltech

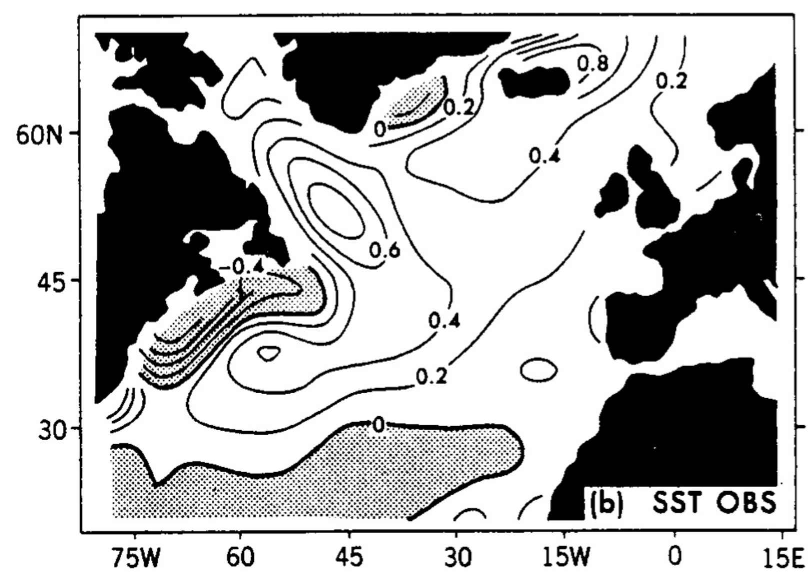
The Atlantic Multidecadal Oscillation (AMO)

SSTA



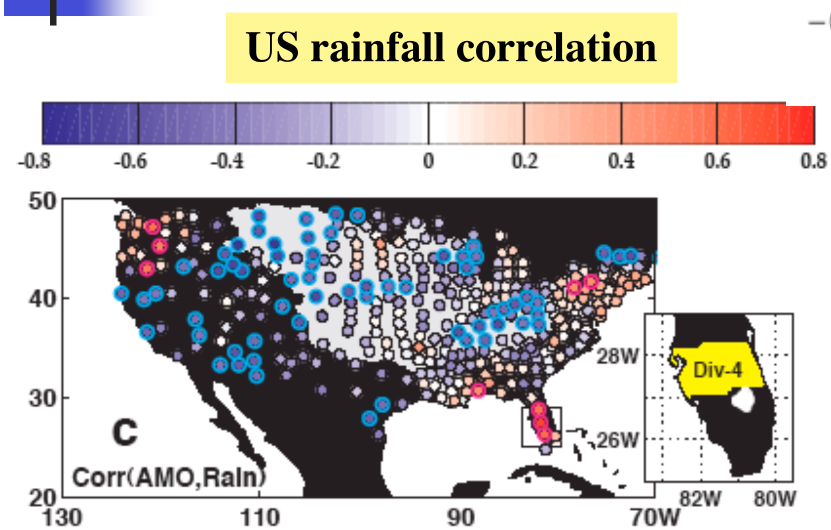
Average SST anomaly over the entire North Atlantic basin

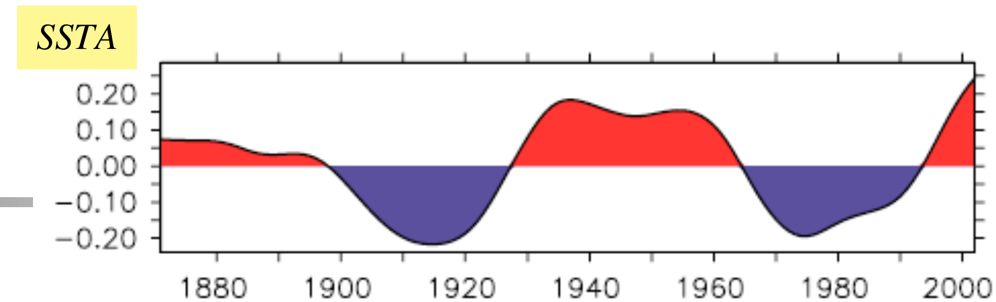
SST (1950-1964) - SST (1970-1984)

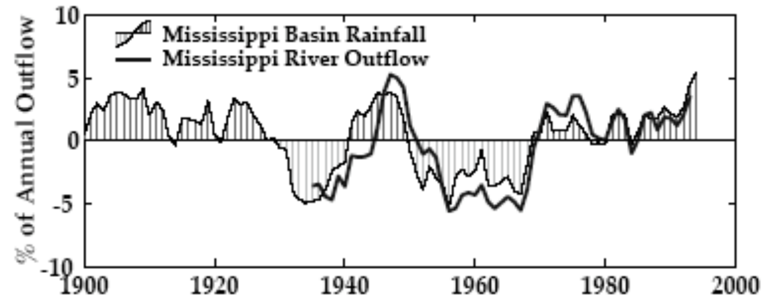


Kushnir, J. Clim, 7, 141, 1994

Importance of the AMO





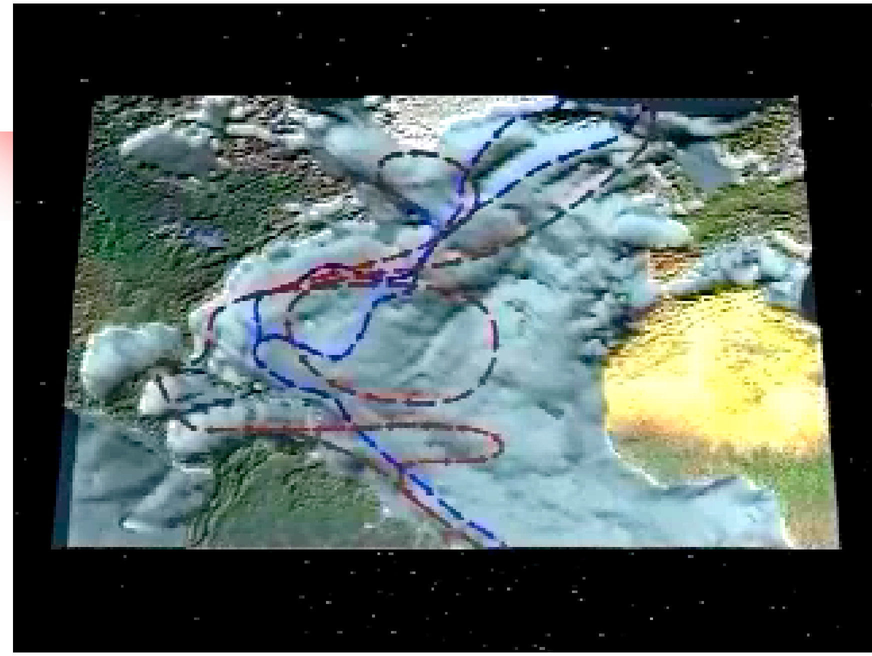


Enfield et al., GRL, 28, 2077, 2001

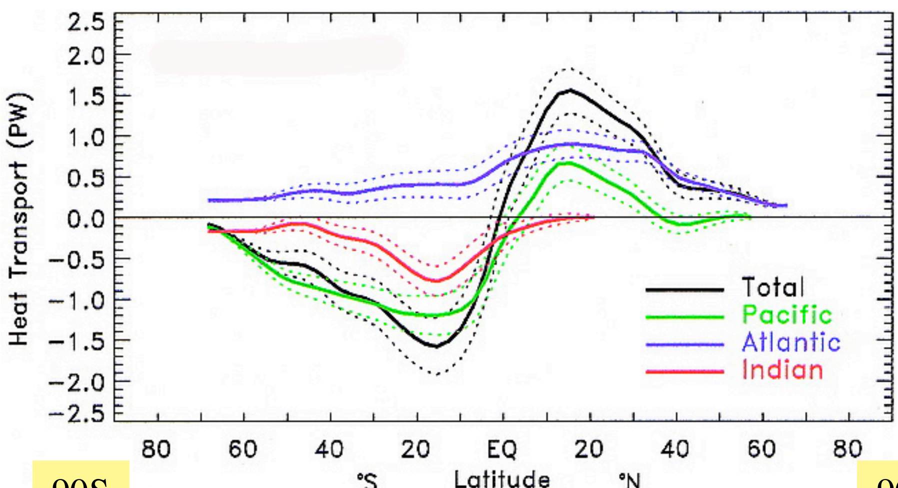
Question: What is the physics of the multidecadal variability in the North Atlantic?

Wanted: explanation for (i) AMO time scale, (ii) AMO pattern

The North Atlantic Ocean Circulation



Heat transport (PW)



90S

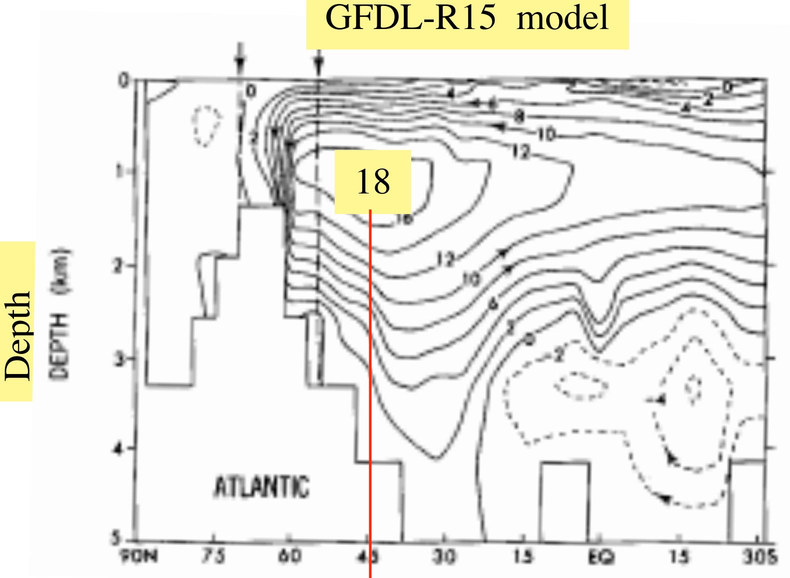
90N

Zonally integrated transport

Meridional overturning streamfunction Ψ

GFDL-R15 model

Depth



18

90N

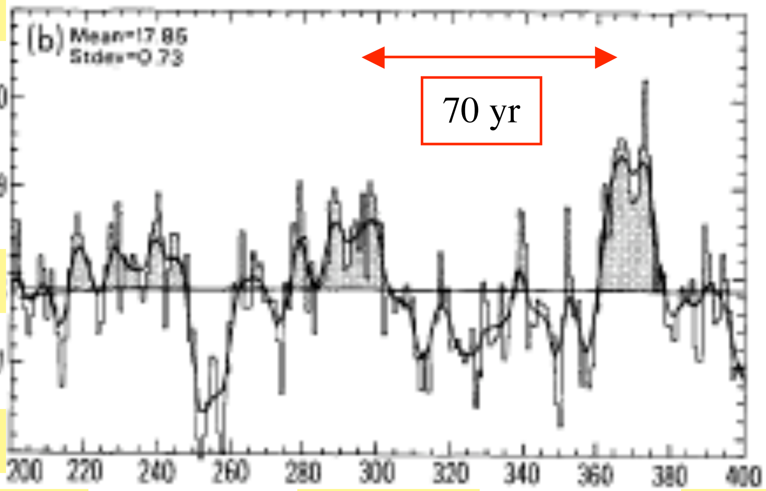
THC-index

30S

1 Sv = 1,000,000 m^3/s

GFDL R 15 climate model results

THC-index



70 yr

21

18

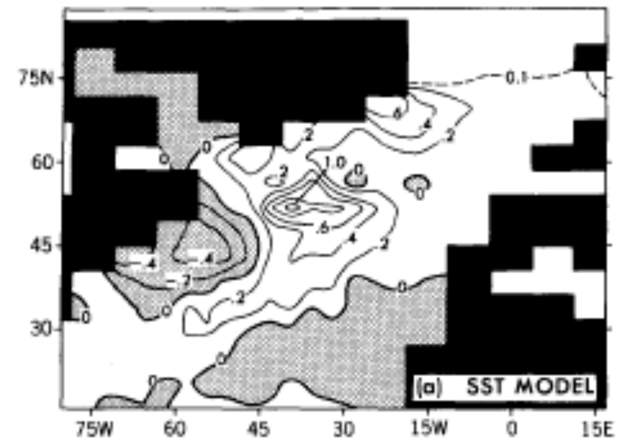
16

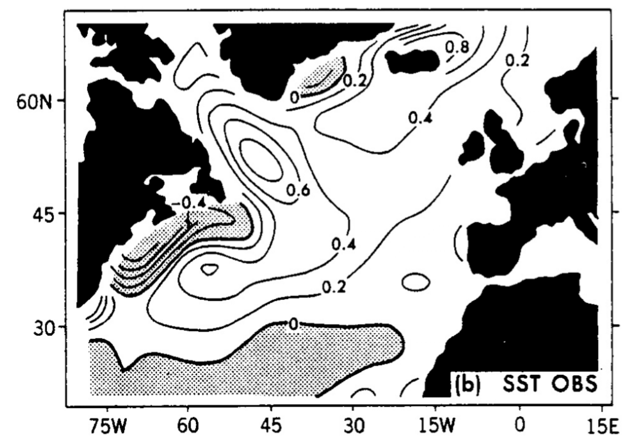
200

Time (yr)

400

SST
High THC index - Low THC index





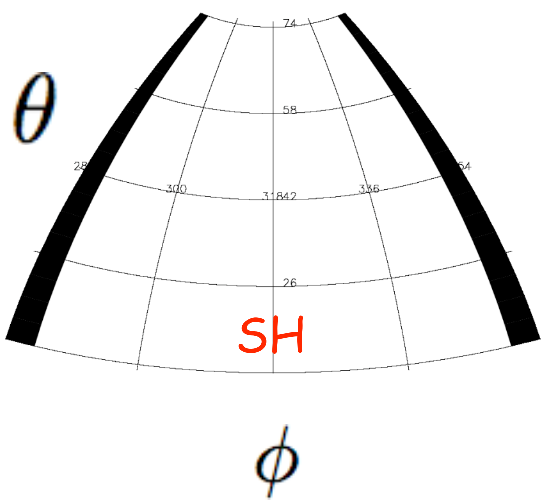
Oceanic grid: 96 x 40 x 12

Atmospheric grid ~ 48 x 40 x 11

Simulation: 1000 yr

Delworth et al., J. Clim 6, 1993, (1993)

Single-sector basin ocean model



$$\rho_0\left(\frac{d\mathbf{u}}{dt} + 2\Omega \wedge \mathbf{u}\right) = -\nabla p - g\rho\hat{z} + \mathcal{F}$$

$$\nabla.\mathbf{u} = 0$$

$$\frac{dT}{dt} = K_H \nabla_H^2 T + K_V \frac{\partial^2 T}{\partial z^2}$$

$$\rho = \rho_0(1 - \alpha(T - T_0))$$

Restoring: $z = 0 : T = \Delta T \; T_S(\phi, \theta)$

or

Flux: $z = 0 : K_V \frac{\partial T}{\partial z} = \frac{Q_H}{\rho_0 C_p}$

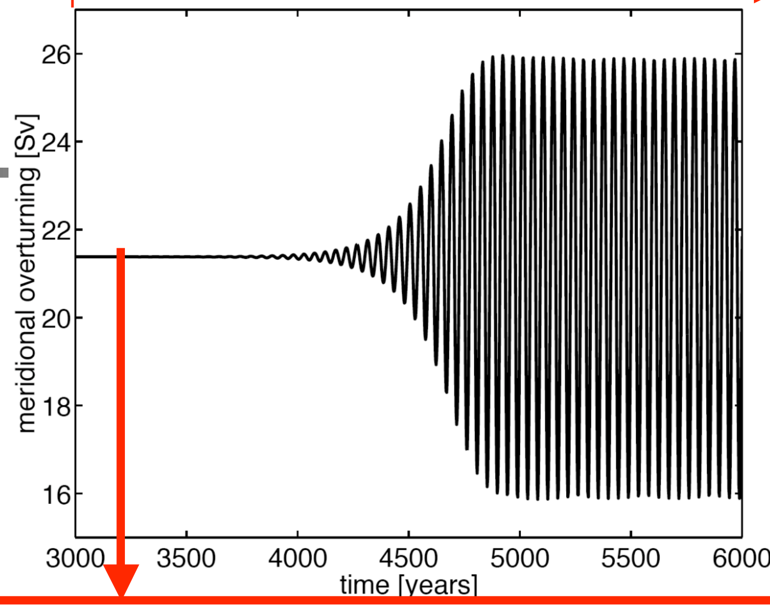
Sector [286,350] x [10,74] (4 degree)
Depth 4000 m (16 levels)

Control parameters: $K_H, \Delta T$

Ocean-only model results

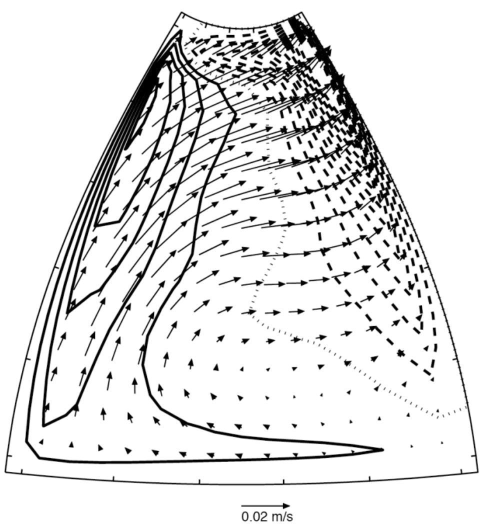
Restoring Conditions *Flux Conditions*

$max \quad \Psi$

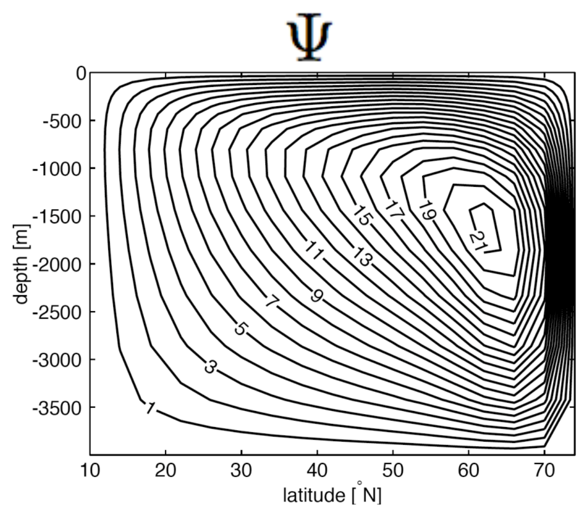


Spontaneous Oscillation:

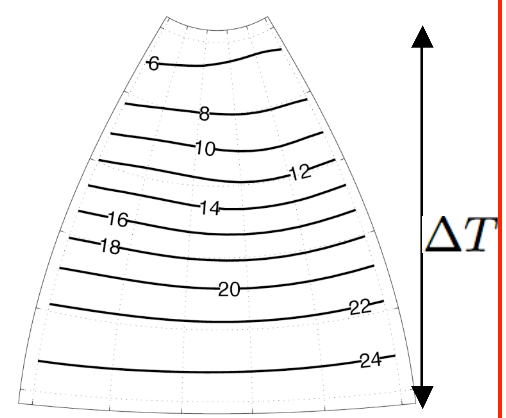
Period ~ 54 year



Surface velocities



Meridional Overturning



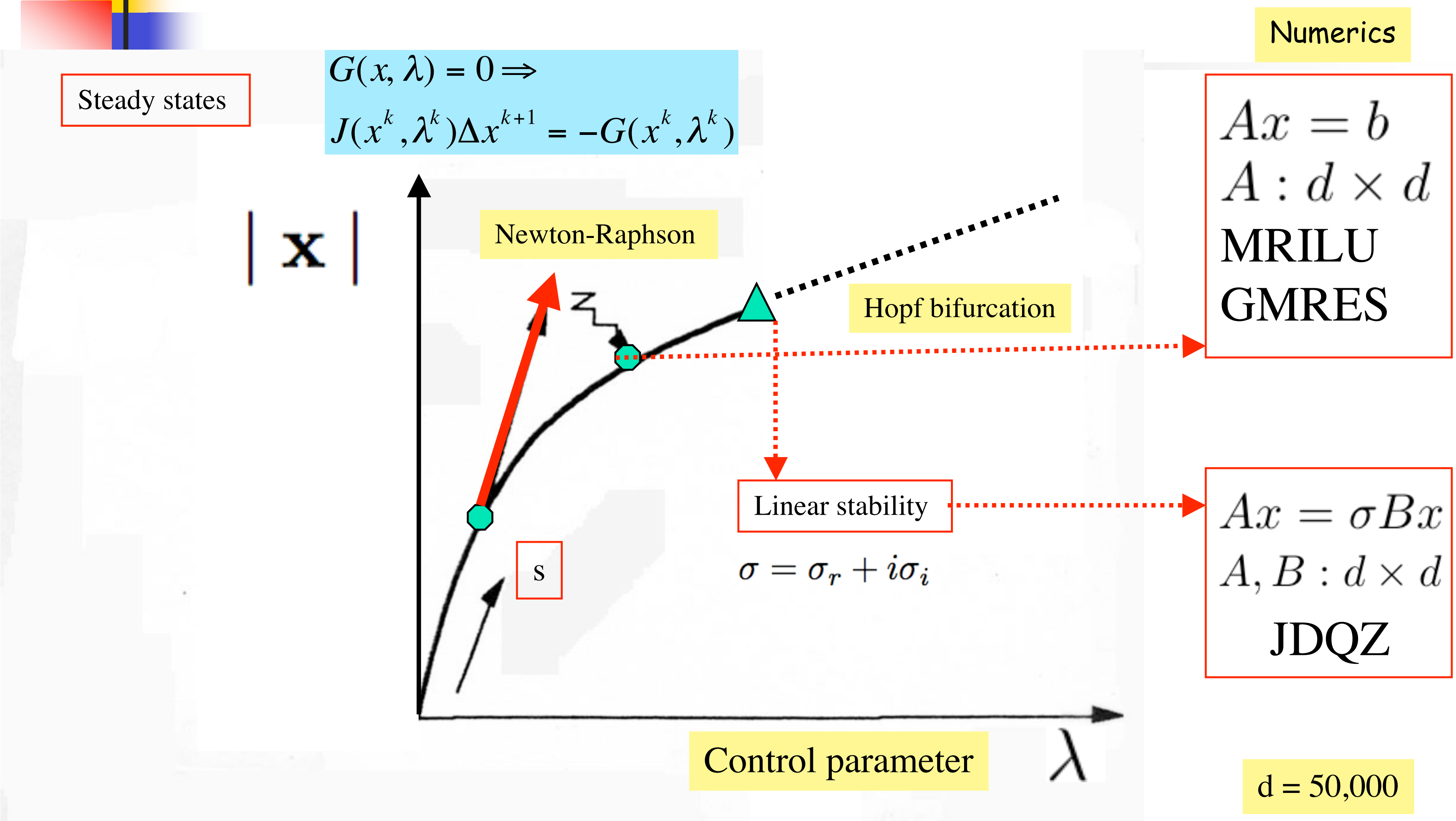
Surface temperature

Specific questions & approach

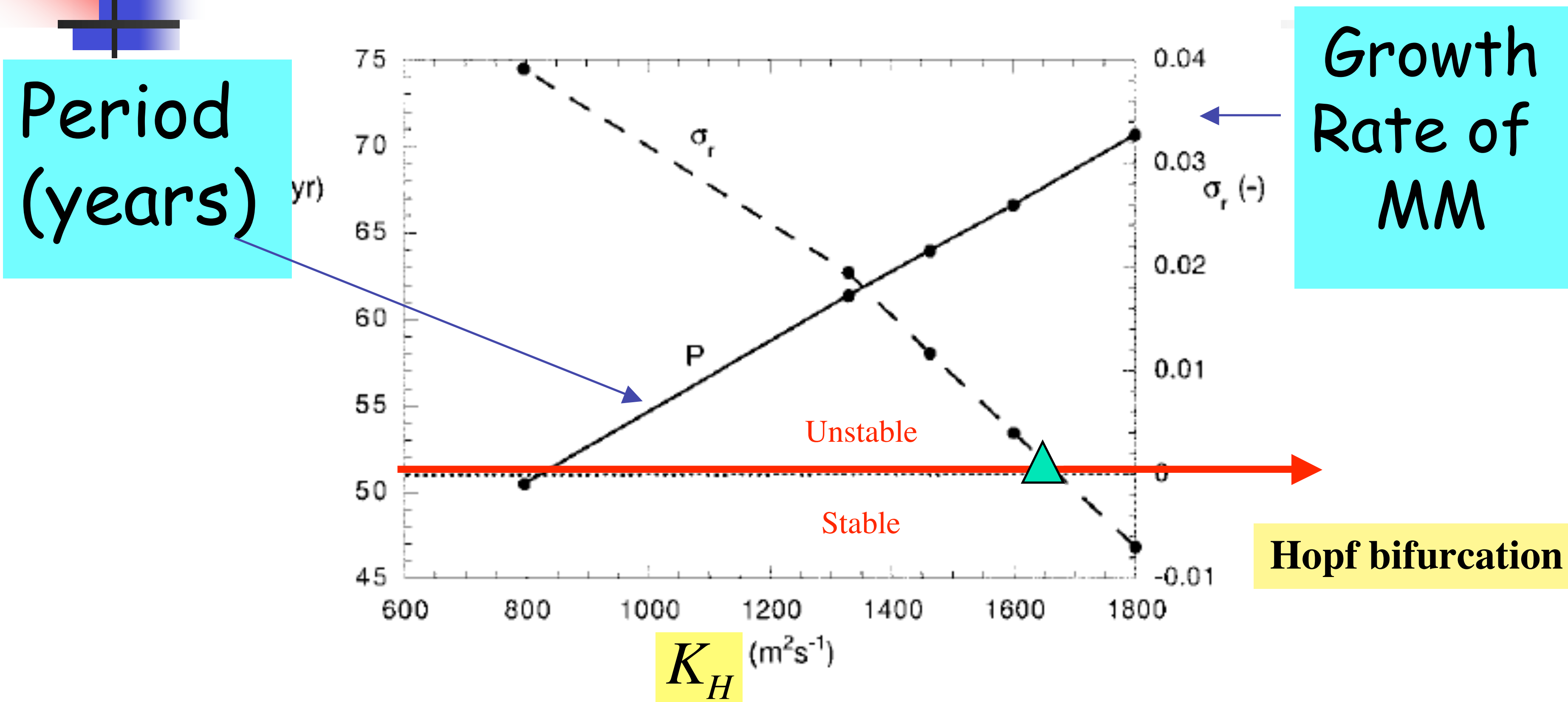
- Does the oscillation appear through an instability of the steady flow to a multidecadal mode (MM)?
  - Physical mechanism of such a MM.
- Do the spatial pattern and time scale of the AMO arise through the presence of such a MM?
  - Consider the MM in more complex models.

Continuation methods

$$M\frac{dx}{dt} + G(x, \lambda) = 0, x \in R^d$$

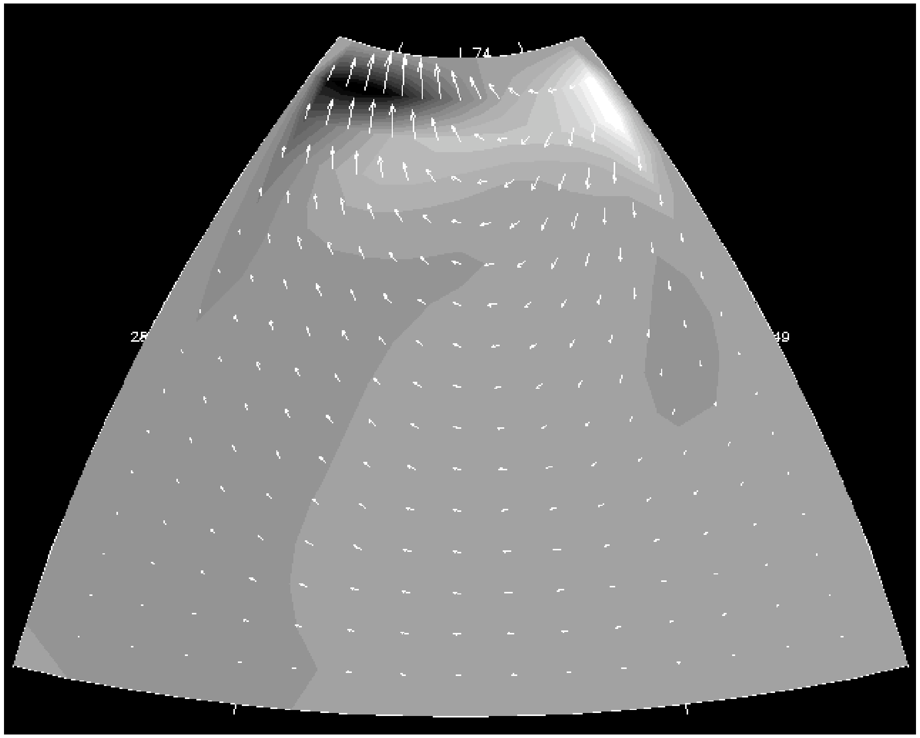


Linear stability of the steady states

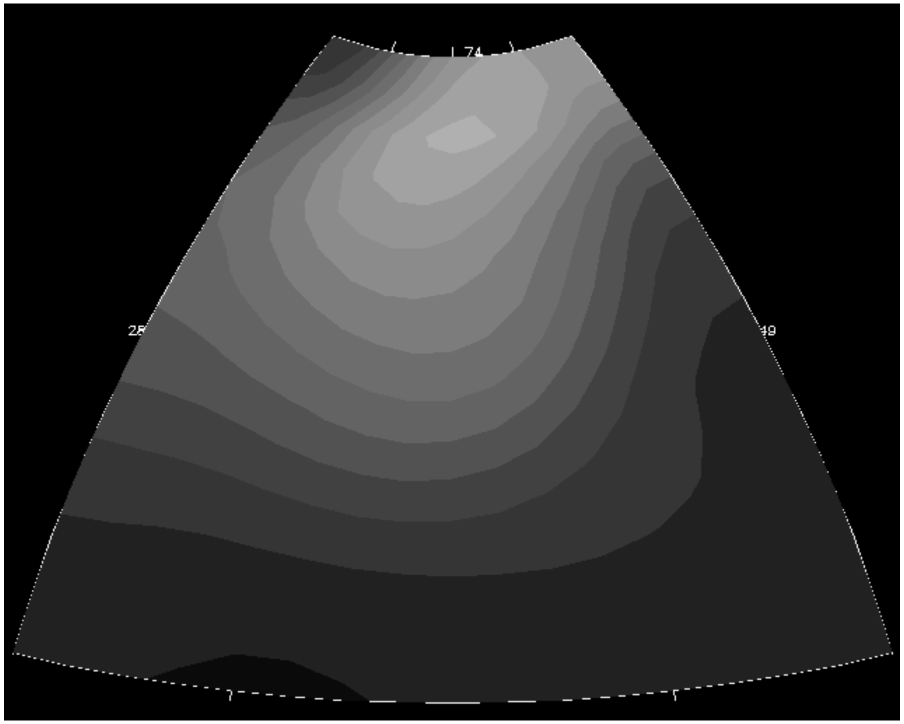


Lateral mixing of heat

Patterns of the MM near Hopf bifurcation



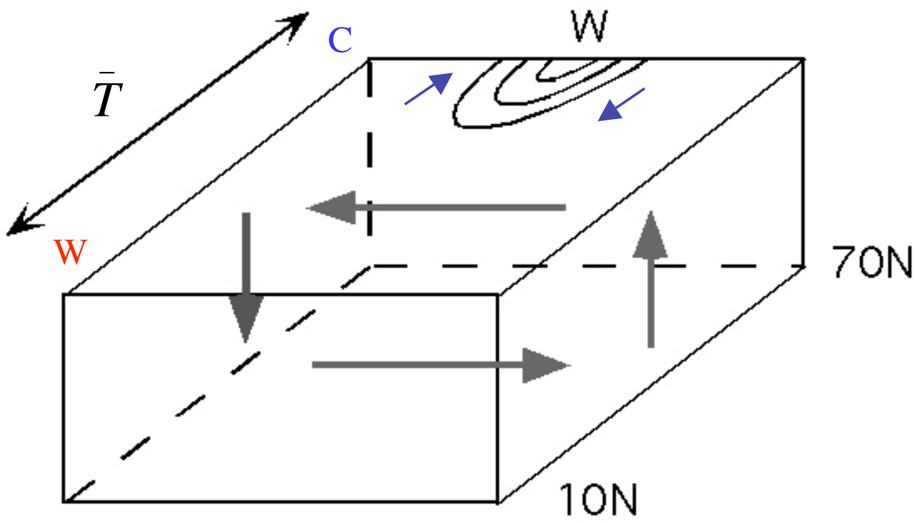
Surface velocity



Surface temperature

Control parameter: Horizontal mixing coefficient of heat, $K_H = 1600\ m^2 s^{-1}$

Physics of the oscillation

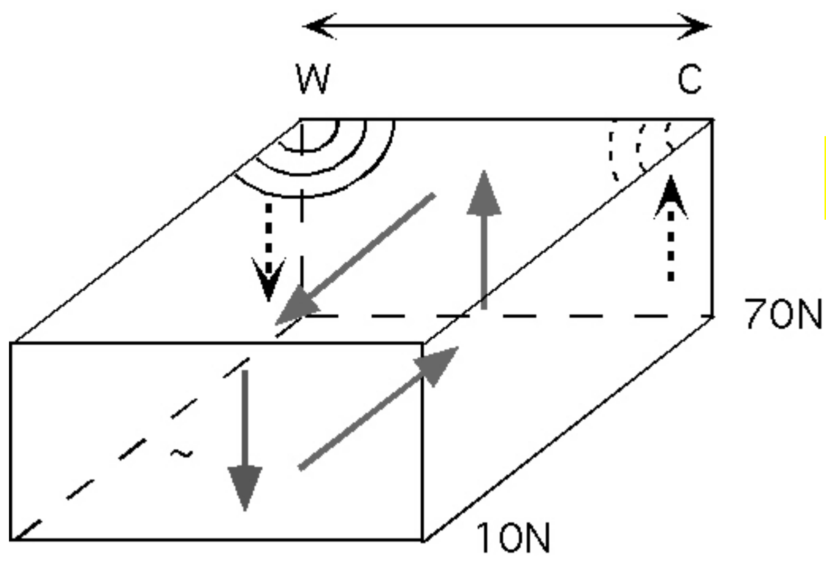


Phase t = 0

Thermal Wind:

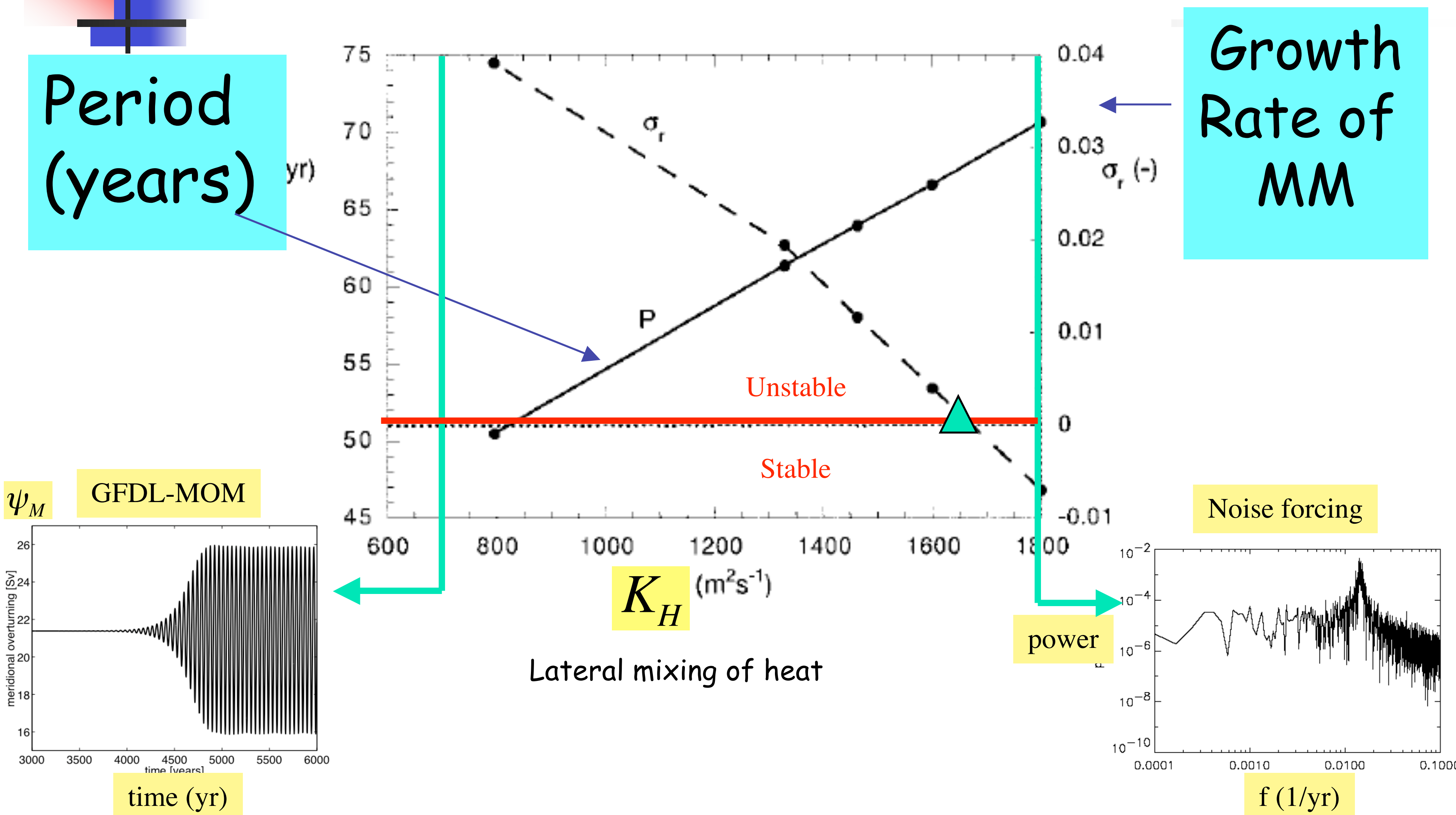
$$\sin\theta \frac{\partial u}{\partial z} \sim -\frac{\partial T}{\partial \theta}$$

$$\sin\theta \frac{\partial v}{\partial z} \sim \frac{1}{\cos\theta}\frac{\partial T}{\partial \phi}$$



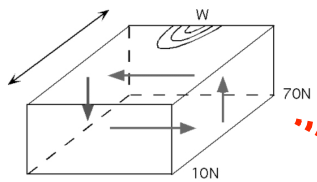
Phase t = P/4

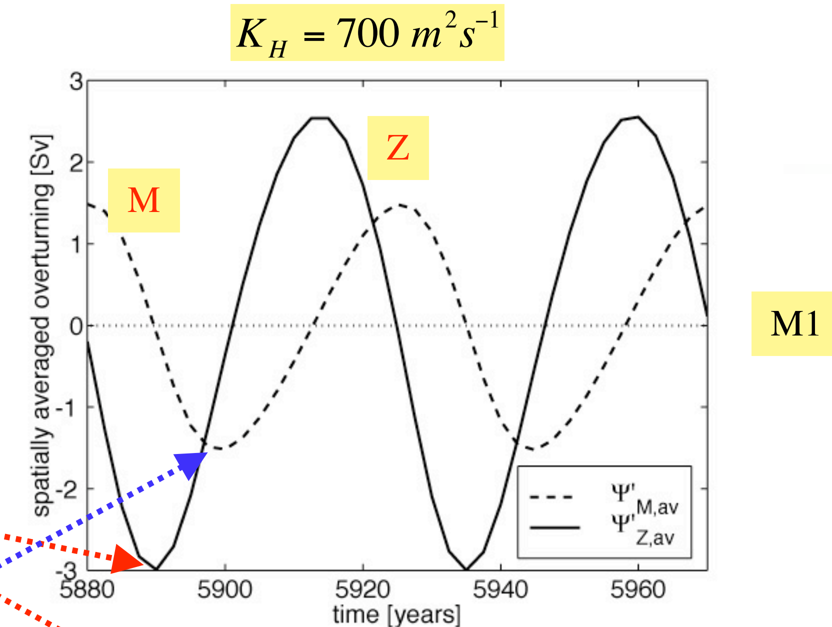
Transient behavior

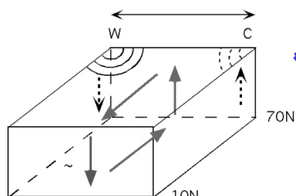


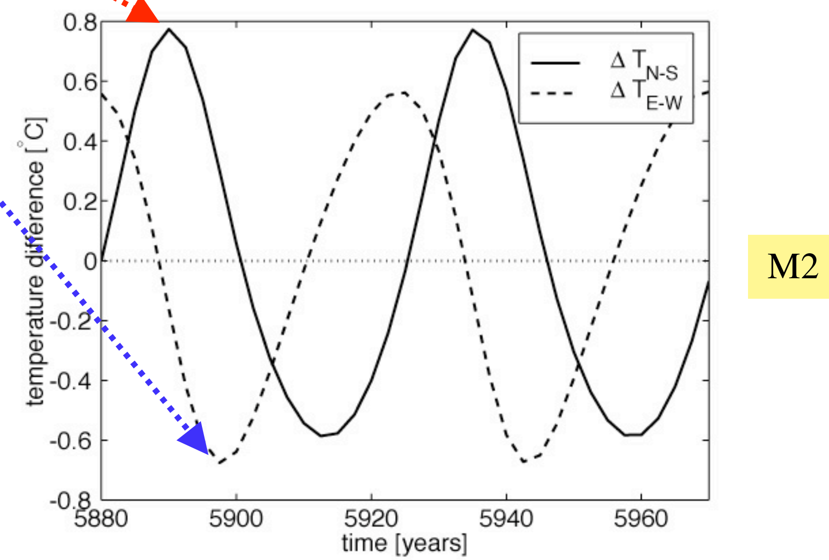
Mechanistic indicators

- **M1**: Phase difference between zonal (Z) and meridional (M) overturning anomalies









- **M2**: Phase difference between E-W and N-S temperature differences

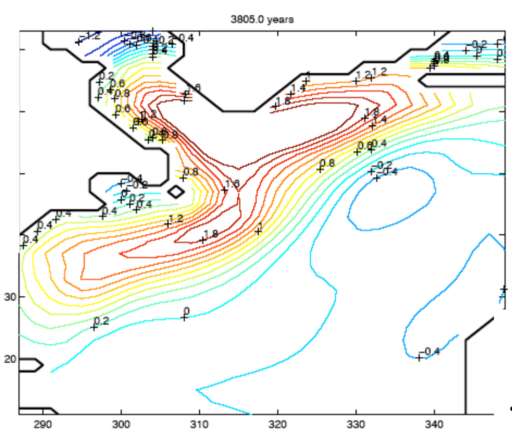
Others: terms in energy balances …

Effects of continents

GFDL-MOM

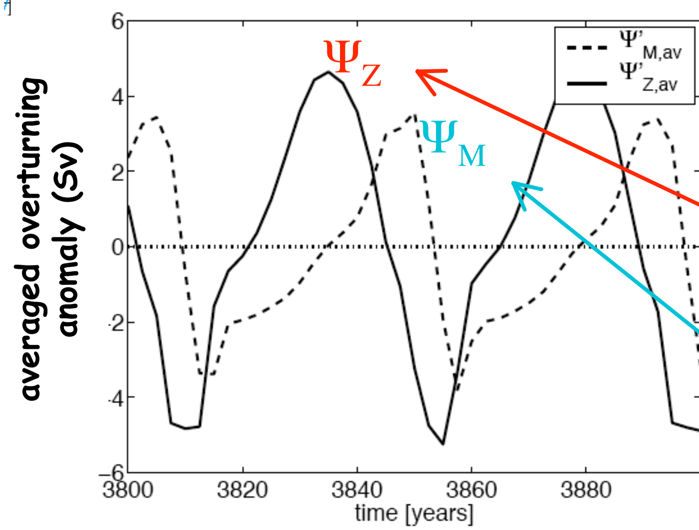
SST (Ψ_M max.) -
SST (Ψ_M min.)

latitude



longitude

P=45 yr

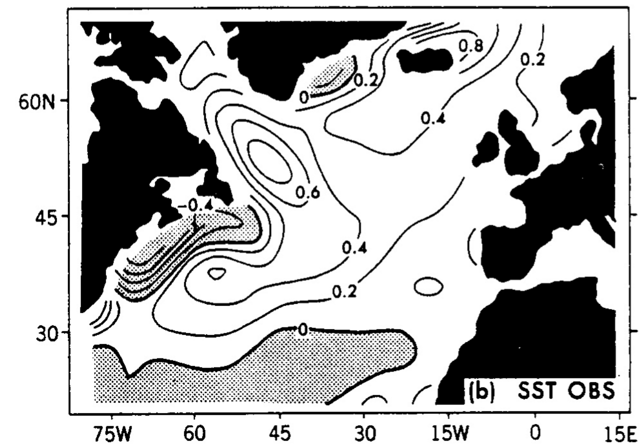


Zonal overturning

Meridional overturning

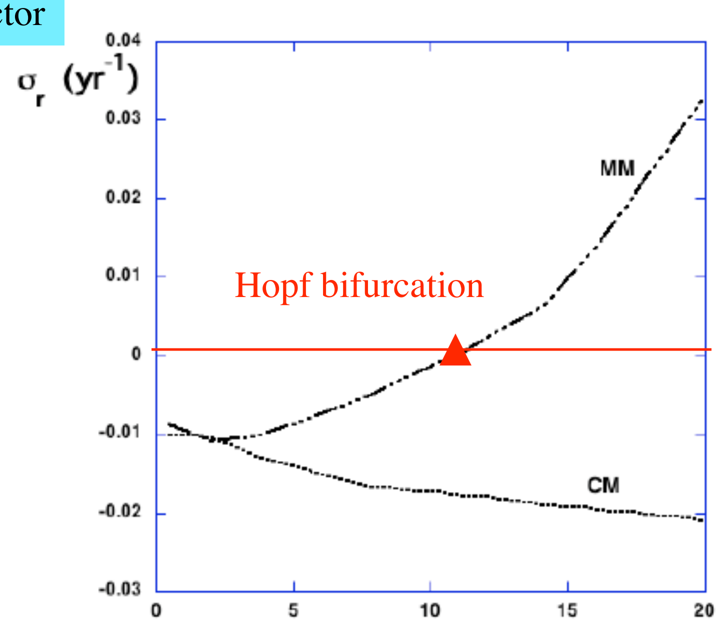
Observations

SST (1950-1964) -
SST (1970-1984)



Spectral origin of the MM

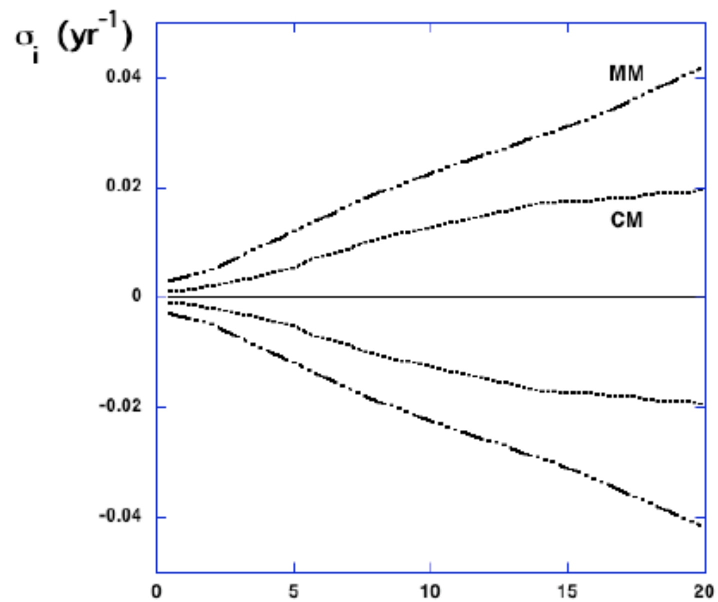
Growth factor



Temperature difference

ΔT

Angular frequency

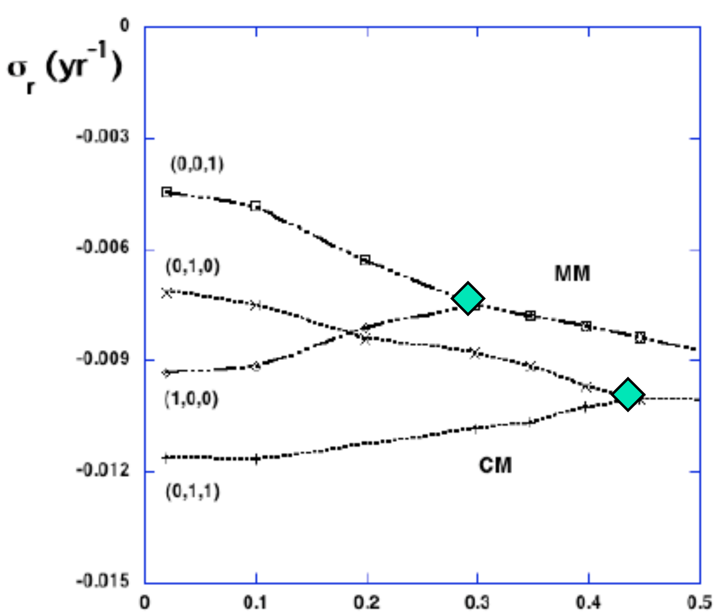


Temperature difference

ΔT

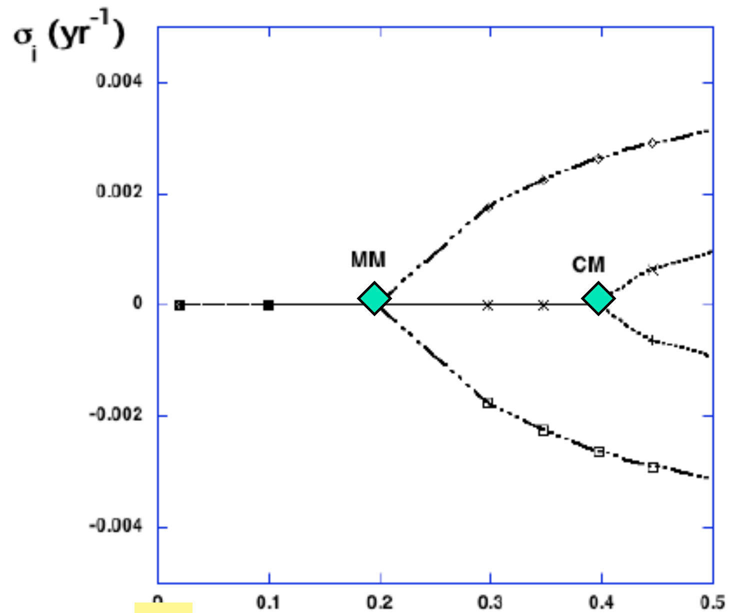
SST-mode merger

Growth rate



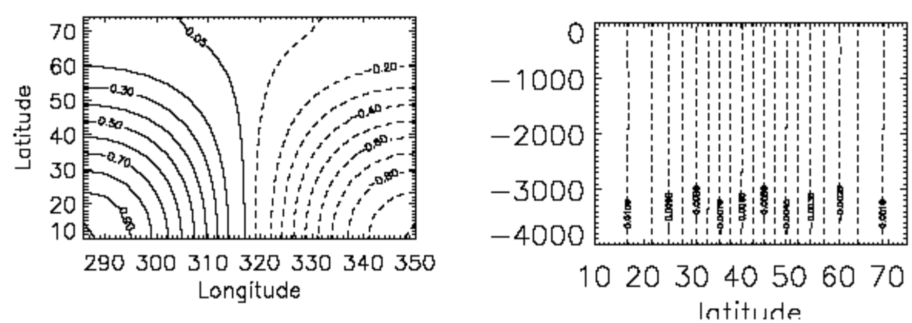
0 ΔT 0.5

Frequency



0 ΔT 0.5

Ex: (1,0,0)



$\Delta T \rightarrow 0$: SST - modes

$$\frac{\partial T}{\partial t} = K_H \nabla_H^2 T + K_V \frac{\partial^2 T}{\partial z^2}$$

+ BC's

Mode mergers provide a framework to understand low-frequency variability of the global ocean circulation

Momentum equations:

$$\mathcal{M}_\lambda \frac{\partial \mathbf{v}}{\partial t} = \mathcal{F}_\lambda(\mathbf{v}, \bar{T}) \qquad \mathbf{v} = \hat{\mathbf{v}} e^{\sigma t} \Rightarrow \mathcal{J}_\lambda \hat{\mathbf{v}} = \sigma \mathcal{M}_\lambda \hat{\mathbf{v}}$$

→ *Ocean dynamics modes: Ex. Rossby Basin modes, Gyre modes*

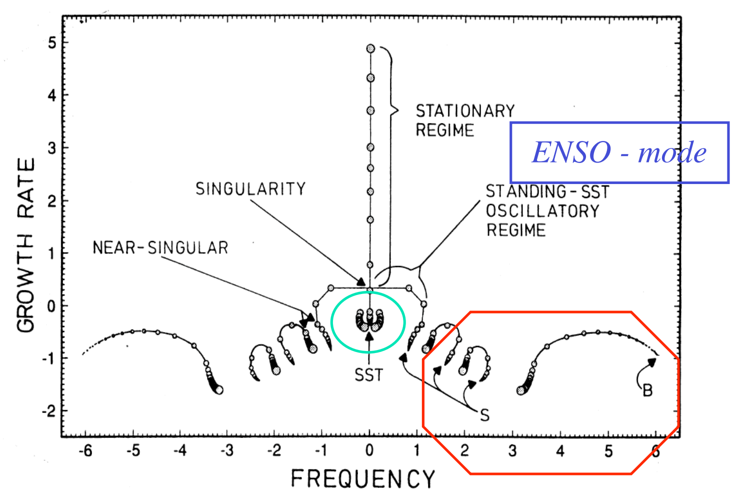
Energy equation:

$$\frac{\partial T}{\partial t} = \mathcal{G}_\lambda(\bar{\mathbf{v}}, T) \qquad T = \hat{T} e^{\sigma t} \Rightarrow \mathcal{I}_\lambda \hat{T} = \sigma \hat{T}$$

→ *Sea surface temperature modes: (SST-modes)*

Prominent example: El Nino mode

(SST mode)



(equatorial dynamics modes)

Jin & Neelin, JAS, 1993

Summary of main points

A multidecadal mode (MM) exists in models of the North Atlantic climate system.

Its spectral origin is an SST-mode merger

Its propagation mechanism is a lagged response of the zonal and meridional flow perturbations due to propagating temperature (density) perturbations.

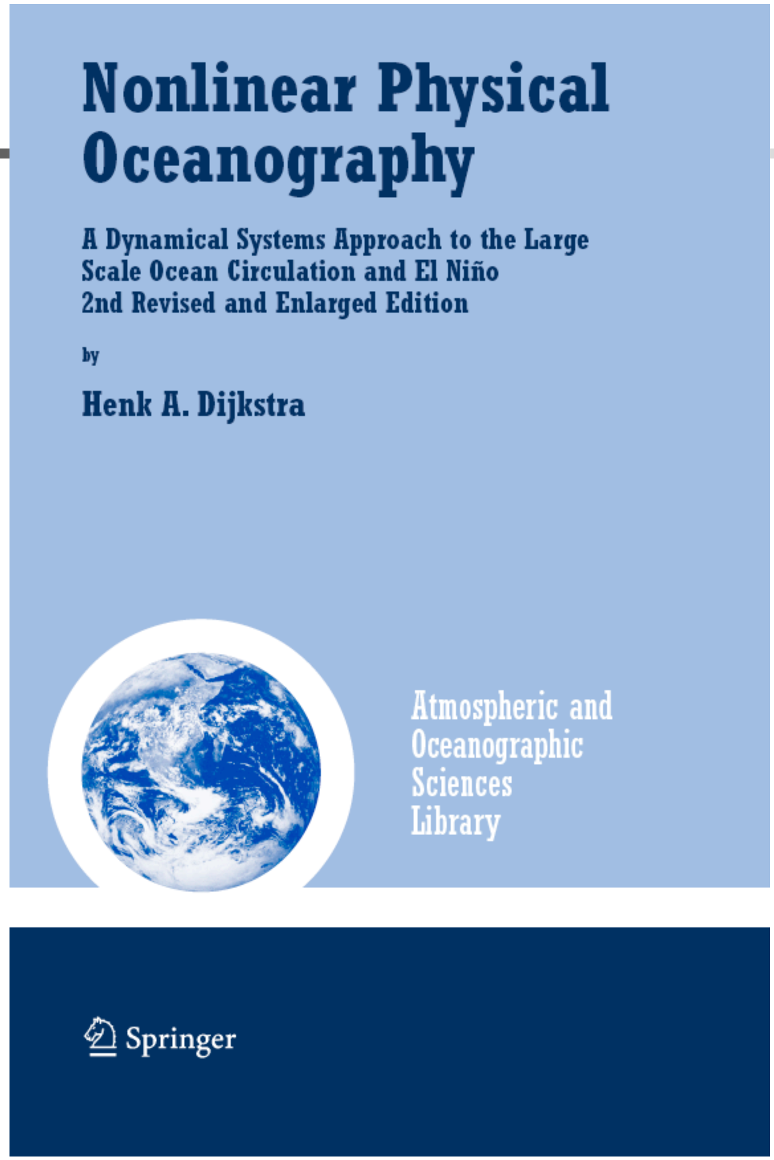
The MM may be an important factor in the AMO:

Time scale: basin crossing time

Pattern: deformation of the pattern of the MM due to the continental boundaries

Atmospheric noise may have a substantial effect on the amplitude of the AMO

Further reading ...



April 15, 2005

Price: $ 89